negligible with the present experimental uncertainties. The relation between the elements of solid angle is:

$$4\cos\theta_{\rm lab}d\Omega_{\rm lab}=\frac{8(\gamma+1)}{[(\gamma+3)+(\gamma-1)\cos\theta^*]^2}d\Omega^*.$$

Again, within experimental accuracy it is sufficient to use the relation obtained by putting $\gamma=1$.

In the moving reference system each particle has a velocity $u$ where

$$u=\gamma v/(\gamma+1).$$

The relative flux is then $2u$. The density of final states is

$$(p^*E_f^*/32\pi^3\hbar^3)d\Omega^*.$$

Here $p^*$ is the momentum of one of the particles and $E_f^*$ is the total final energy:

$$p^*=M\gamma v/[2(\gamma+1)]^{\frac{1}{2}},\quad E_f^*=2M[\tfrac{1}{2}(\gamma+1)]^{\frac{1}{2}}.$$

Inserting these quantities into the Born approximation formulae one finds the net effect is to multiply the non-relativistic expression for the cross section by $\frac{1}{2}(\gamma+1)$ and to replace the non-relativistic wave vector $\mathbf{k}$ by a wave vector $\mathbf{k}^*$ corresponding to the momentum $\mathbf{p}^*$. Even at 350 Mev the difference between $\mathbf{k}$ and $\mathbf{k}^*$ is very small. Hence, the total "kinematic" relativistic effect is to multiply the cross section by $\frac{1}{2}(\gamma+1)$. For 350 Mev this factor is 1.18, while at 260 Mev it is 1.14.

Since comparable dynamic relativistic effects are to be expected,[18] there is little point to try for anything better than about 20 percent accuracy.

*Notes added in proof.*—(1) It has been kindly pointed out to us by Dr. Christian that while the $S$–$P$ interference vanishes the $P$–$D$ does not. While small, this contributes an asymmetry to the $n$–$p$ scattering which is of the same order as that observed. However, the sign of the interference term turns out to be the opposite of that observed. This suggests the above sign determination of the $LS$ term is wrong. With the "odd" exchange dependence this will not affect the deuteron. However, the connection with the work of M. Mayer is then lost.

(2) Professor Serber has emphasized to us that irrespective of the $p$–$p$ effects the $LS$ term does not *lower* the $n$–$p$ total cross section which calculation always gives as too large compared with experiment.

(3) Preliminary exact calculations indicate that a considerably smaller range of the spin-orbit term is needed to achieve a really flat 350-Mev cross section. This would mean the constants given in this paper may need large alteration and the possibility of simultaneously fitting the 30-Mev data may be lost. These exact calculations will be reported elsewhere.

[18] H. J. Bhabha, Proc. Roy. Soc. **A166**, 501 (1938); H. Snyder and R. Marshak, Phys. Rev. **72**, 1253 (1947).

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# The Cross Section for Photo-Disintegration of the Deuteron at Low Energies

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Precision measurements have been made of the photo-disintegration of the deuteron with the gamma-rays of $Ga^{72}$ and $Na^{24}$. Relative cross sections have been measured at 2.51, 2.62, and 2.76 Mev. Calibration of the sources gave absolute cross sections at 2.62 and 2.76 Mev.

## I. INTRODUCTION

THE variation with energy of the photoelectric and photo-magnetic cross sections of the deuteron is essential data for the determination of the parameters of the nuclear forces. So far measurements of the total cross sections $\sigma_T=\sigma_e+\sigma_m$ have been made by several groups [1–8] using $\gamma$-rays of quantum energy 2.62, 2.76, 6.3, and 17 Mev.

The measurement of these cross sections falls naturally in two parts: the determination of the number of $\gamma$-quanta emitted per unit time by the source and the number of photo-disintegrations produced by this source in a system containing heavy hydrogen.

The disintegrations are now usually counted by observing the photo-protons either in an ionization chamber counter or in a photographic plate. These methods have the advantage of being independent of a neutron standard needed for older methods relying on the counting of photo-neutrons. Recently, deuterium filled ionization chamber counters with electronic collection have been developed sufficiently to allow a precision of 1 percent in comparing the number of photo-protons produced by $\gamma$-rays of different energy.

Several methods can be used for determining the number of $\gamma$-quanta emitted from the source. In the case of the 2.62 Mev $\gamma$-rays emitted by RdTh, one can use the results of Ricoux[9] or Winand[10] giving the number of disintegrations per second of a RdTh source which gives the same ionization as 1 mg of radium in an ionization chamber of the Curie type. Unfortunately,

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[1] J. Chadwick and M. Goldhaber, Nature **134**, 237 (1933).
[2] H. Halban, Nature **141**, 644 (1938).
[3] Wilson, Collie, and Halban, Nature **162**, 185 (1948); **163**, 245 (1949).
[4] Snell, Barker, and Sternberg, Phys. Rev. **75**, 1290 (1949).
[5] Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).
[6] J. Van Allen and N. Smith, Phys. Rev. **59**, 618 (1941).
[7] Barnes, Stafford, and Wilkinson, Nature **165**, 70 (1950).
[8] H. Wäffler and S. Youmis, Helv. Phys. Acta **22**, 414 (1949).
[9] J. Ricoux, J. de phys. et rad. **8**, 388 (1939).
[10] L. Winand, J. de phys. et rad. **10**, 361 (1939).

neither author indicated the accuracy of his measurements. The agreement however is good (~1 percent), but both methods involve an accurate knowledge of the branching ratio of ThC in order to obtain the number of 2.62 Mev $\gamma$-quanta.

The determination of the absolute number of $\gamma$-quanta produced by a source can be made with an accuracy of 1 to 2 percent in the case of the 2.76-Mev $\gamma$-line of radiosodium,[11] $Na^{24}$. The $\gamma$-ray spectrum is sufficiently simple[12] to allow standardization either by the coincidence method or by the ionization method developed by Gray.[13] For $Na^{24}$ these two methods agree within the limits of measurement.

When using a radiosodium source standardized by the coincidence method and a radiothorium source standardized by the Ricoux-Winand method three of us found[3] the ratio for the total cross section of the photo-effect at 2.76 Mev and 2.62 Mev to be $1.05\pm0.08$.

An error was discovered in the radiothorium calibration, however, since the Ricoux factor of 1.09, which should be applied to convert the source strength in milligrams radium equivalent to millicuries, was omitted. The corrected ratio (taking into account the new value for the decay constant of radium) was $1.12\pm0.08$, a result lower than the value of 1.21 which is predicted by theory. This discrepancy seemed especially interesting since the ratio of the two cross sections turns out to be fairly independent of the range of force, and the refinements of different theories. Thus Hansson and Hulthén[14] obtain values varying between 1.19 and 1.22. Bethe and Longmire[15] have calculated $\sigma_m$ and $\sigma_e$ for $\gamma$-ray energies of 2.62 and 2.76 Mev. In their phenomenological treatment they make use of recent data for the binding energy of the deuteron, neutron-proton and proton-proton scattering cross sections. From their figures for $\sigma_T$ one equally obtains $\sigma_{2.76}/\sigma_{2.62}=1.19$. Similar calculations have been made by Halpern and Woodward.[15]

For this reason it was felt that the measurements should be extended to lower energies.

Radiogallium, $Ga^{72}$, emits a $\gamma$-ray spectrum which includes as its highest member a $\gamma$-ray of energy 2.51 Mev.[16,17] Unfortunately, both the coincidence method and Gray's method of standardization fail in practice when the spectrum is complicated, so that hitherto this convenient source has not been available for absolute measurements.

At this point cooperation between a group of workers in the Nobelinstitut för Fysik in Stockholm and a group of the Clarendon Laboratory in Oxford seemed promising. The procedure which became possible through the collaboration of the two groups, and which will be described below, made measurements with the $Ga^{72}$ line feasible. Furthermore, it will in future allow one to determine the relative number of $\gamma$-quanta of 2.51 Mev, 2.62 Mev, and 2.76 Mev emitted by any set of sources of RdTh, $Ga^{72}$, and $Na^{24}$ by comparing them on the substandard ionization chamber.

Throughout the work two sources each of $Ga^{72}$ and $Na^{24}$ provided by the Isotope Division of A.E.R.E. Harwell were used. After irradiation they were placed in copper tubes identical with the container of the RdTh source of 13.2 mg radium equivalent described later. These sources were compared on the substandard ionization chamber to an accuracy of 0.1 percent. The number of photo-protons produced by the RdTh source and one of each of the $Ga^{72}$ and $Na^{24}$ sources in the same deuterium filled ionization chamber counter was determined in Oxford. Each source has only one $\gamma$-ray line with sufficient energy to produce photo-protons of *measurable energy.*

The other set of sources was flown to Stockholm where the relative number of $\gamma$-quanta of each of the three lines was determined with a $\beta$-ray spectrograph. The combination of the measurements on the $\beta$-spectrograph and deuterium filled ionization chamber give the relative cross sections for the photo-effect of the deuteron for the 2.51-, 2.62-, and 2.76-Mev $\gamma$-ray lines. Absolute values were obtained at 2.62 Mev and at 2.76 Mev by calibrating the sources.

## II. THE CURIE-TYPE SUBSTANDARD IONIZATION CHAMBER

All of the sources used were compared with a radium standard, and where possible with each other, on a substandard ionization chamber. This chamber is a copy of that used in the Curie Institute in Paris,[18] it is a shallow chamber 52 cm in diameter with 1 cm of lead for filtration on top. The exact location of the source on top of the lead is of small importance; there is only a 0.1 percent change in ionization if the source is displaced by 5 cm. Thus the chamber is ideal for the reproducible measurement of the extended sources which have been used. The electrometer was used as a null instrument and has proved to be very stable;[19] it is possible to compare two sources of approximately equal strengths to an accuracy of 1 part in $10^4$. Two sources of very unequal strength can be compared to an accuracy of 1 part in $10^3$.

## III. MEASUREMENT OF THE RELATIVE INTENSITIES OF THE $\gamma$-RAYS AT 2.504($Ga^{72}$), 2.618 (ThC″) AND 2.757 Mev ($Na^{24}$)

Since the hard $\gamma$-rays here concerned are emitted together with a rather large number of other $\gamma$-lines in the different $\gamma$-spectra it is necessary to use a method

[11] J. L. Putman, Brit. J. Radiol. **23**, 265 (1950).
[12] O. T. Seaborg and I. Perlman, Rev. Mod. Phys. **20**, 585, 1948.
[13] L. H. Gray, Brit. J. Radiol. **22**, 677 (1949).
[14] I. F. E. Hansson and L. Hulthén, Phys. Rev. **76**, 1163 (1949).
[15] H. A. Bethe and C. Longmire, Phys. Rev. **77**, 647 (1950). See also I. Halpern and W. M. Woodward, M.I.T. Report.
[16] S. K. Haynes, Phys. Rev. **74**, 423 (1948).
[17] Mitchell, Zaffarano, and Kern, Phys. Rev. **73**, 1424 (1948).
[18] E. Curie, J. de phys. et rad. **2**, 975 (1912).
[19] R. Wilson and G. R. Bishop, Proc. Phys. Soc. London **42**, 257 (1949).

which allows a complete separation of the different $\gamma$-components so that each $\gamma$-line can be studied separately. A high resolution $\beta$-ray spectrometer is naturally best suited for this purpose and if the photo-effect produced by the $\gamma$-rays in a thin metal foil is studied one has the advantage of dealing with well-defined electron lines. The other two effects, which could have been used, *viz.*, the Compton effect and the pair formation effect, give continuous secondary electron distributions and are less suited for very precise intensity measurements.

The photo-electron method has already been quite extensively used for $\gamma$-ray intensity measurements and was actually introduced by Ellis and Aston as early as 1930, but it should be pointed out that with a few exceptions these previous measurements have never aimed to reach an accuracy better than 10 or even 15 percent. One is faced with rather serious difficulties when the demand for accuracy, as in the present case, is raised to one or two percent. Some of these difficulties will be discussed here.[20]

### A. Thickness of Electron Converter

Photo-electrons expelled from the converter will straggle during their passage through the converter due to inelastic collisions and radiation losses.[21] Apart from a general line shift the photo-lines get broader and soon the line width caused by this effect exceeds that of the spectrometer, if this is adjusted for the high resolving power necessary in this case. Some of the electrons may even be scattered out from the line and get lost in the continuous distribution of Compton electrons. The need for a thin converter is therefore obvious. On the other hand, at these high energies the photo-effect is so much reduced in magnitude that the necessary demands for high statistical accuracy on each point on the photo-line can only be satisfied if a compromise is made in choosing the converter thickness.

As shown by Ellis and Aston[22] and later by Richardson[23] the other extreme possibility, that of using a practically infinitely thick converter, has the advantage of being more easily calculable than is the method of using a thin converter. Though in many cases this circumstance may be useful, it is still difficult to know to what accuracy Richardson's formula can be applied without making special experimental checks. There is, however, still one good argument against the use of the thick converter method in the present case. It is experimentally well known that the *form* of the Compton electron distribution changes somewhat if a thick lead foil is placed above a converter of low $Z$ value, for example, copper. Thus it is very hard to separate in an accurate way a photo-line from the continuous Compton distribution, when the line is not completely resolved from the latter distribution, even if the investigation is made with and without a lead foil.

It was found that a lead foil of 20 mg/cm$^2$ was of a suitable thickness. According to Fig. 1, showing the photo-lines of ThC″ at 2.62 Mev and obtained with the double focusing spectrometer, it is possible to resolve completely the $K$ photo-line both from the $L$ photo-line *and* from the corresponding Compton electron distribution, and still have a sufficiently good counting rate. The line width at this energy is only slightly more than that given by the spectrometer and the size of the sample.

### B. Anisotropy in the Photoelectric Emission

The direction of emission of the photo-electron relative to the direction of the quantum, being 90° at $E_\gamma=0$, will be more and more forward as energy increases, since momentum is transferred from the $\gamma$-quantum to the electron. Since the spectrometer only accepts electrons with a large forward component the intensity of the harder $\gamma$-rays may be overestimated unless one uses the differential photoelectric cross section when evaluating the data. This may happen especially for low energy $\gamma$-rays with "good" geometry (canalized $\gamma$-rays and small dimensions of converter) and extremely thin lead foils, where no smearing-out effects occur. The most probable angle for emission can be calculated[24] and it is found, in agreement with experiment,[25] that this angle is small at the energies relevant to this work. Thus Latyshev[25] finds the angle to be 9° at 2.62 Mev. This angle varies very little inside our energy range from 2.52 to 2.76 Mev. Furthermore, the geometry of our sample and converter is able to

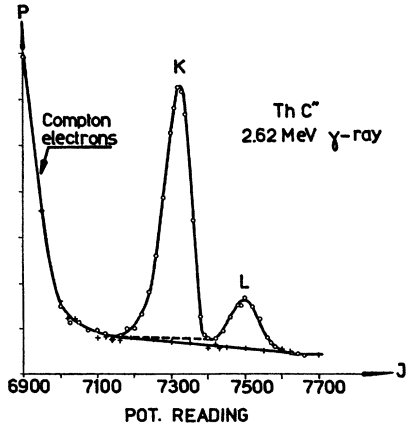


FIG. 1. Photo-lines of ThC″.

[20] For a more complete discussion see H. O. W. Richardson, Proc. Phys. Soc. London **63**, 234 (1950), particularly dealing with the Ellis-Aston method. See also G. Latyshev, Rev. Mod. Phys. **19**, 132 (1947) and Deutsch, Elliott and Evans, Rev. Sci. Inst. **15**, 178 (1944).

[21] See W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1944), p. 219 (5) and p. 221 (9).

[22] C. Ellis and M. Aston, Proc. Roy. Soc. **A129**, 180 (1930).

[23] H. O. W. Richardson, reference 20.

[24] A. Sommerfeld, *Atombau und Spektrallinien* II, p. 494. Compare K. Siegbahn and H. Slätis, Arkiv. f. Mat. Astr. o. Fys. **32A**, No. 9 (1945).

[25] G. Latyshev, Rev. Mod. Phys. **19**, 132 (1947).

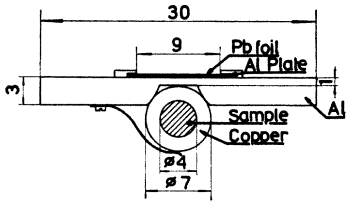


FIG. 2. Arrangement of sample and lead converter.

smear out any anisotropic effect to a fairly large extent, since the sample is placed quite close to the lead foil and the area of the sample ($\phi=4$ mm, $l=18$ mm) is smaller than that of the foil ($d=9$ mm, $l=20$ mm).

### C. Arrangement of Samples and Converter

In order to be able to reproduce the position of the sample relative to the lead converter in an accurate way the following arrangement was used (Fig. 2). All three samples were enclosed in copper capsules of identical geometry and the active material in each case was enough to fill the capsule completely. The capsules were placed in a cavity in the sample holder and were held in the correct position by a spring. The lead converter, supported on a 0.2-mm aluminum plate, could be attached to the holder on a slide. In this way the position of the well-defined volume of the samples was always fixed relative to the lead converter within a tenth of a mm. Special checks were made to see if the intensity of the photo-lines were influenced by rotation of the samples or changed of $\pm 1$ mm up or down, but no such effects could be observed.

### D. Accuracy of the Theoretical Photoelectric Cross Section for Lead

If it is assumed that the experimental conditions are such that the complications due to straggling effects in the converter and the anisotropic photoelectric emission can be neglected, the intensity of a $\gamma$-line is simply given by:

$$J_\gamma = kJ_K/\sigma_K, \tag{1}$$

where $k$ is a spectrometer constant, depending on the transmission and sample geometry, $J_K$ is the intensity of the $K$ photo-line (i.e., area under the peak, when the number of counts in each point has been divided by the corresponding $H\rho$ value and $\sigma_K$ is the photoelectric cross section for the $K$ shell. The accuracy of our final results will depend on how well known the variation of $\sigma_K$ within our energy range can be considered to be. Though the photo-effect is in principle quite well understood, there exists no closed theory, which can be evaluated to give the photo cross section at all $Z$ values and over the entire energy range. Several formulas have been deduced[26] based on various approximations, such as the Born approximation, which may be applied in different energy ranges and for different $Z$ values, but most of these are fairly inaccurate in the energy region concerned here. An exact calculation by Hulme *et al.*[27] is valid for all $Z$ values and energies, but cannot be evaluated numerically at energies greater than 2 Mev. There is still another formula due to Hall[28] which is mathematically not quite rigorous, but which was shown by Hume *et al.* to give very satisfactory results at sufficiently high energies. Thus, at 1.1 Mev the cross section deviates from the exact value of Hulme by only 6 percent. We are therefore inclined to trust the Hall formula as capable of giving accurately the *variation* of the cross section within our small energy range without introducing theoretical uncertainties. According to Hall's formula the cross sections for lead at 2.51, 2.62, and 2.76 Mev are 1.252, 1.184, and $1.113\times10^{-24}$ cm$^2$, respectively. Evans and Evans[29] have given the cross section for lead based on a critical compilation due to Davisson.[30] The absolute value of the cross section at 2.62 Mev has been measured by Davidson and Latyshev[31] and it agrees well with that obtained from Evan's curve, which at this energy was calculated by means of Hall's formula. At lower energies the curve is based on other approximations.

In view of the fact that our lead converter could not be considered to be infinitely thin and also in view of our special geometry, an experiment was performed in order to check the validity of (1) for our particular case. The two sodium $\gamma$-lines are known to be emitted in cascade and to have the same intensity. By measuring the areas of the two photo-lines the relative values at the photo cross section at 1.38 and 2.76 Mev can be measured for our geometry, that is, we get an experimental check over a very much larger energy range than that with which our main experiment is concerned. We obtained consistently a value for $\sigma_{1.38}/\sigma_{2.76}$ which was 15 percent higher than that given by Evans' curve. The reason for this departure from the theoretical curve is somewhat puzzling, since any possible small influence of the converter thickness as well as the anisotropic emission should be expected to go in the other direction. We may therefore not disregard completely the possibility of a failure of Eq. (1) to yield accurate intensities over the entire energy range.[32] Even if we assume this to be the case it is evident that the correction would be very small within our narrow energy range. Instead of having a total variation of cross section between 2.51 to 2.76 Mev of 12 percent the sodium experiment could indicate an additional 2 percent. It is preferable, however, to use the theoretical values for our problem since

[26] See W. Heitler, reference 21, p. 125.

[27] Hulme, McDougall, Buckingham, and Fowler, Proc. Roy. Soc. **149**, 131 (1935).

[28] H. Hall, Phys. Rev. **45**, 620 (1934).

[29] R. D. Evans and R. O. Evans, Rev. Mod. Phys. **20**, 305 (1948).

[30] C. M. Davisson, thesis, M.I.T. We are very much indebted to Professor R. D. Evans for discussion on this point.

[31] Davidson and Latyshev, J. Phys. U.S.S.R. **6**, 15 (1942).

[32] It is interesting to note that the empirical relationship due to Gray (Proc. Camb. Phil. Soc. **27**, 103 (1931)) gives a value for $\sigma(1.38)/\sigma(2.76)$ which is 15 percent *higher* than our value. This relation is however based entirely on data below 1 Mev.

it must be assumed that the ideal conditions for the experiments are better satisfied at our high energies than at lower.

### E. Experimental Procedure and Results

The measurements were performed with the large double focusing spectrometer ($\rho=50$ cm), described elsewhere.[33] The magnetic field measuring system has now been considerably improved and permits an accuracy in the field setting of 0.01 percent. The current through the Helmholz coil is measured by compensating the voltage developed across a manganin resistance in a temperature-controlled oil bath.

The $K$ photo-lines of the hard $\gamma$-lines of $Ga^{72}$, ThC″ and $Na^{24}$ are shown in Figs. 3–5. One interesting new fact was immediately recognized. The 2.51-Mev Ga line is double. This is evident from the values of the half-width of the three photo-lines in Figs. 3–5. In the case of ThC″ and $Na^{24}$ this is constantly the same in all measurements (1.10 percent), whereas a large departure from this value is found for $Ga^{72}$ (1.42 percent). The two lines are situated 0.6 percent apart and it is possible to resolve them completely in the spectrometer by making suitable arrangements, which will be discussed by one of us on a later occasion.[34] In the term scheme worked out by Mitchell *et al.*[16,17] there is actually room for a transition of this energy, i.e., between the fourth excited level and the ground state, in addition to the one already given between the sixth and the first excited levels. The new line therefore to a certain extent confirms the complicated scheme presented by Mitchell *et al.*

The fact that the $\gamma$-line at 2.51 Mev is double will not introduce any complications for the interpretations of the experiments on the number of photo-protons performed in Oxford. It is necessary, however, to consider this circumstance when the areas under the $K$ photo-lines of lead are not completely resolved, in the sense that the intensity in the valley between is not zero. Nevertheless, it was found practicable to let the dotted line in Fig. 1 correspond to the base of the $K$ photo-lines. When comparing the lines of $Na^{24}$ and ThC″ this small simplification could in principle not introduce any error. Because of the double line character with the correspondingly greater line widths for $Ga^{72}$ the valley between the $K$ and $L$ lines is situated somewhat higher in that case giving too small an intensity for the photo-line. The correction for this was experimentally determined and was found to be very small (=1 percent).

The three samples were always measured twice and interchanged in the following sequence: RhTa, Na, Ga, Na, Ga, RaTh. The total time required for a series of measurements was about 14 hours.

Besides the intensities, the energies of the lines were determined relative to the 2.618 Mev of ThC″ in the following way. From the dotted base-line a vertical line was drawn to the apex of the line. On the half-height of this a horizontal line was drawn cutting the photo-line in two points. The midpoint between these two points was chosen as representing the position of the line. When this procedure was used, it was found that the accuracy in defining the lines was greatly enhanced as compared with the more direct ways of trying to find the top of the lines, for example. The reproducibility for the sodium and ThC″ lines in three independent measurements was actually found to be 1 in $10^4$. In the case of ThC″ and sodium this made a very accurate energy comparison possible. In the case of the double gallium line, the measurement of the precise energy value is naturally less clear and should only be interpreted as some weighted mean value of the two lines. Those values are taken to calculate the theoretical photo-disintegration cross section. The energy loss due to straggling in the lead foil for the three lines is almost independent of energy in this range[35] and the correction can be neglected. Taking the energy of the ThC″ $\gamma$-line to be 2.618 Mev[35] the energies of the $Na^{24}$ and $Ga^{72}$ lines were found to be: $E_\gamma=2.757\pm0.001$ and 2.504 Mev, respectively.

## IV. ABSOLUTE SOURCE CALIBRATIONS

### A. Radiosodium ($Na^{24}$)

The radiosodium source was calibrated by the $\beta$–$\gamma$-coincidence technique developed by Dunworth[36] and improved by Putman.[11] Some calibrations were made at A.E.R.E. Harwell, using Putman's apparatus and other using a similar apparatus in Oxford.

The dilutions were made by dissolving the sodium carbonate source and weighting out an aliquot of solution. The sources were calibrated by separate coin-

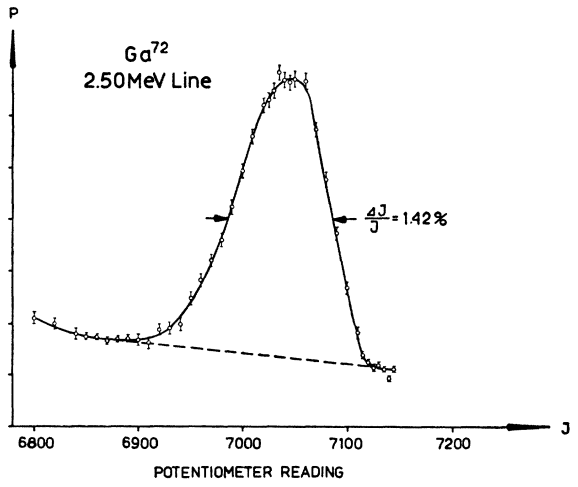


FIG. 3. $K$ photo-line of the hard $\gamma$-ray of $Ga^{72}$.

[33] Hedgran, Siegbahn, and Svartholm, Proc. Phys. Soc. London (1950).
[34] A. Hedgran (to be published).
[35] Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).
[36] J. R. Dunworth, Rev. Sci. Inst. **11**, 167 (1940).

cidence runs on 4 different aliquots. The over-all errors (statistical and weighing) are about 0.5 percent. There are several possible sources of systematic error. Multiple counts in the Geiger counter are suppressed by using a multivibrator quenching unit,[37] A.E.R.E. type 1014A. Other spurious counts probably introduce less than 0.1 percent error. The $\beta$–$\gamma$-angular correlation[38] is less than 1 percent. The 4.14-Mev cross-over $\gamma$-ray is not found[39] to 3 parts in $10^7$ and there is less than 1 percent of a high energy $\beta$-ray.[12] If each of these effects were present to the limits given above they would together alter the absolute calibration by less than 0.5 percent.

Putman points out that the correction applied for the $\gamma$-rays counted by the $\beta$-counter is uncertain, since the efficiency of the $\beta$-ray counter for $\gamma$-rays changes when an aluminum absorber (used for suppressing the $\beta$-rays) is placed in front of the source. This effect is moreover dependent on the position of this aluminum absorber. This can cause an understimate of the source strength by 1 percent; an auxiliary experiment was performed to determine this correction more accurately.[39a] It was found that in our geometry this change of efficiency was 6 percent, which was exactly compensated by the absorption of $\gamma$-rays in the aluminium screen.

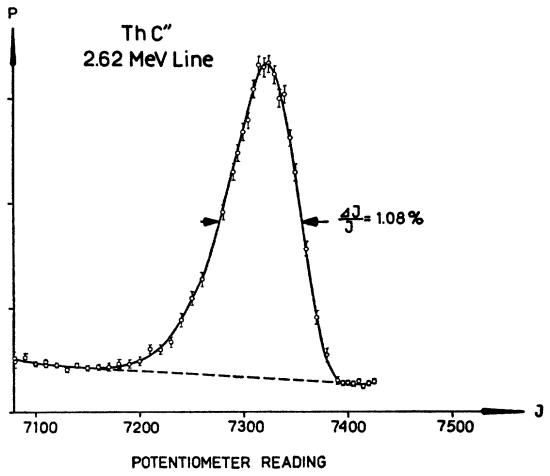


FIG. 4. $K$ photo-line of the hard $\gamma$-ray of ThC''.

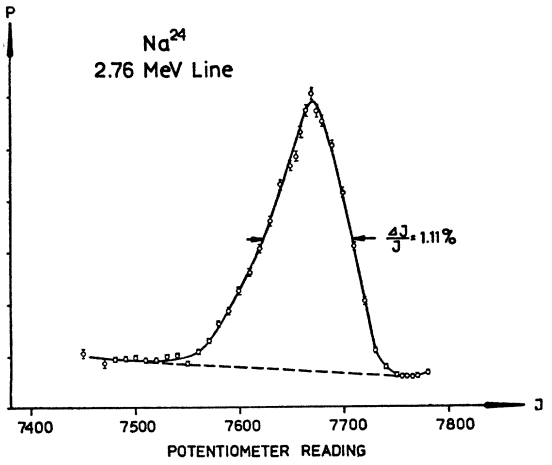


FIG. 5. $K$ photo-line of the hard $\gamma$-ray of $Na^{24}$.

### B. Radiothorium

The radiothorium source was calibrated by using the results of Ricoux[9] and of Winand[10] as reinterpreted by Bouchez[40] in the light of later values for various physical constants. Ricoux measured the total ionization produced by the $\alpha$-particles from a Th(B−C′−C″) source and Winand measured the total heat produced by the $\alpha$-particles. We compare the radiothorium source with a radium standard on our substandard ionization chamber (Section II). The accuracy of this calibration (in terms of the number of 2.62-Mev $\gamma$-ray quanta) we estimate to be about 2 percent; much of the error arises from the uncertainty in the branching ratio ThC′—ThC″. The branching ratio taken is 0.34 atom of ThC″ to 1 of ThC; this is a mean of the values of Albrecht[41] and Kovarik and Adams.[42]

### C. Photo-Proton Counting. The Counter

The number of photo-protons was measured by placing the sources near an ionization chamber counter filled with deuterium to a suitable pressure. The rate of counting of photo-protons was measured with a statistical accuracy of 0.5 percent for each source. The counting rates were corrected for decay of the sources using the decay periods of 14.90 hr. for $Na^{24}$ and 14.08 hr. for $Ga^{72}$.[16,39]

The counter used is shown in Fig. 6. The counting volume is defined by a spherical high voltage electrode, 4 cm diameter, 0.2 mm thick, spun from aluminium. The collecting electrode is shielded with glass except when inside this high voltage electrode. A plot of the field inside shows that the counting volume is equal to the geometrical volume of the sphere to within 0.1 percent. The geometrical volume was measured by filling with water and weighing. The outer pressure-containing cylinder acts also as a guard ring. Photo-protons produced in the gas between the pressure cylinder and the high voltage electrode are not counted; but there is a certain sensitivity for counting the photo-neutrons produced in this volume. A correction of 0.1 percent was subtracted from the count to allow for this effect.

The source is mounted rigidly on the counter and

[37] Cooke-Yarborough, Florida, and Davey, J. Sci. Inst. **26**, 124 (1949).
[38] Grace, Allen, and Halban, Nature **164**, 538 (1949).
[39] Bishop, Wilson, and Halban, Phys. Rev. **77**, 416 (1950). A new lower limit for the 4.14-Mev cross-over $\gamma$-ray has been found since publication.
[39a] R. W. Parsons and C. H. Collie, Brit. J. Radiol. (to be published).
[40] R. Bouchez, J. de phys. et rad. (1949).
[41] E. Albrecht, Zits. Akad. Wiss. Wien IIa **128**, 925 (1919).
[42] A. F. Kovarik and N. J. Adams, Phys. Rev. **54**, 40 (1938).

the distance can be measured to better than 0.1 percent. For the relative measurements, the sources were placed in a source holder which was in the same position for each source, so that even this small inaccuracy does not arise. A correction has to be made to the inverse-square law because of the finite sizes of the source and counter. A simple integration yields the formula.

$$\text{mean}\left(\frac{1}{p^2}\right)=\frac{1}{p^2}\left(1+\frac{a^2}{5p^2}-\frac{x^2+y^2}{3p^2}\right),$$

where $p$ is the distance from the center of source to the center of the counter, $a$ is the radius of the counter's spherical electrode, and $2x$ and $2y$ are the linear dimensions of the rectangular source. The sources used were smaller and more accurately defined than those used by some of us previously, due to the higher specific activity now available.

### D. The Amplifier

The pulses of ionization are only just above the background noise from the amplifier when sources of radio-gallium ($Ga^{72}$) are used, so that a special low noise preamplifier was necessary.[43] This was used in conjunction with an amplifier A.E.R.E. type 1008. The pulses were analyzed by a single-channel kick-sorter, and the counter and amplifier were calibrated as a single unit by measuring the pulse-height distribution of the photo-protons from the disintegration of deuterium by radiothorium $\gamma$-rays. It was thus established that the pulse height distribution conformed to the distribution to be expected from the spread of energy of the protons,[44] and from spread of pulse height by noise, positive ion effects, and wall effect. These will be discussed individually later. Once the energy scale had been established the cross-section measurements were made by counting all photo-protons above a certain bias level with a simple discriminator. The counters were operated with about 5 kv between the electrodes, at which potential the pulse height was approximately saturated. Details of the counter testing and filling procedure adopted are described elsewhere.[45]

### E. Pressure Measurement

The counter pressures used varied. For the absolute measurements only sources of radiosodium and radiothorium were used, and at 8 atmos. pressure the secondary electron background brought the amplifier noise up to the point where the pulses could be just separated from noise. The voltage pulse at the grid of the first tube has an average value of 60 $\mu$volts. This is reduced to 30 $\mu$volts by the pulse-shaping circuits while the r.m.s. noise is 12 $\mu$volts. For the relative measurements with $Ga^{72}$ (which gives photo-protons of lower energy)

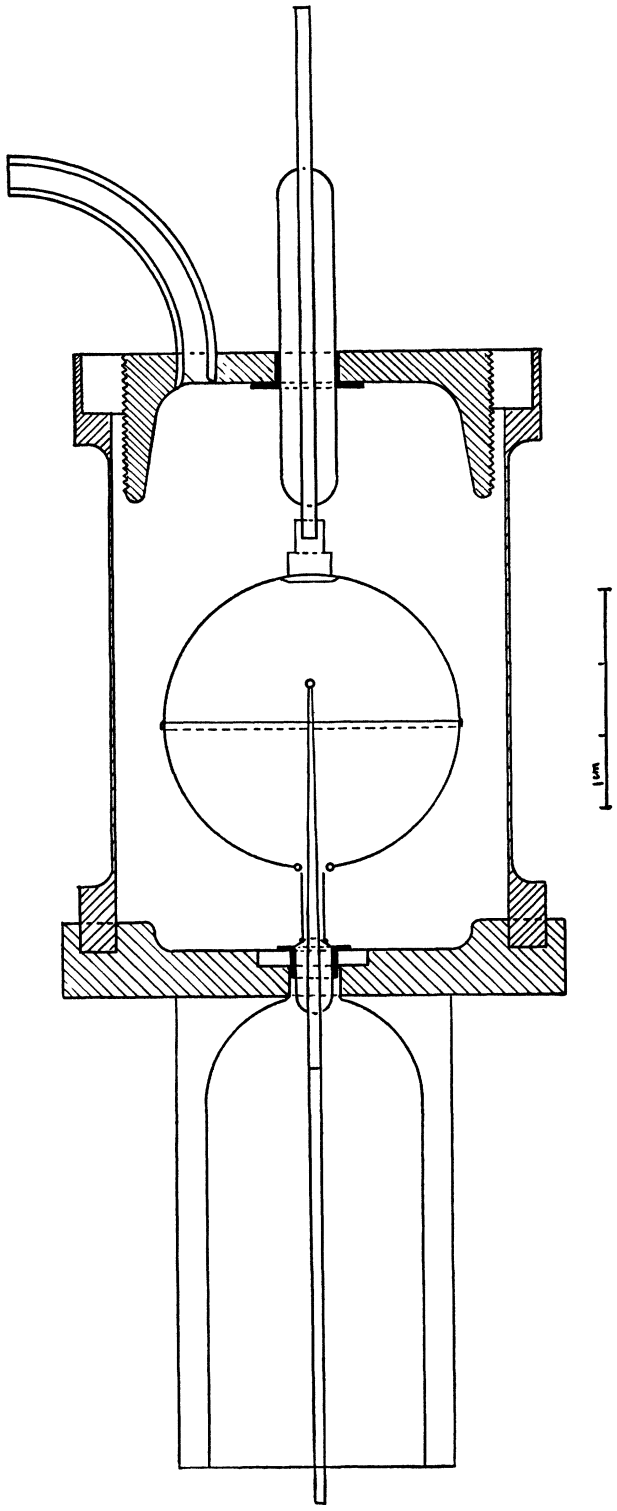


FIG. 6. Schematic diagram of the counter.

[43] R. Wilson, Phil. Mag. 41, 66 (1950).

[44] This spread in energy is due to the conservation of momentum. Photo-protons moving in the direction of the $\gamma$-ray have more energy than those moving in the opposite direction. We have found that the kick-size distribution represents at least qualitatively the angular distribution of the photo-protons. A quantitative development of this method is now being attempted.

[45] Wilson, Beghian, Collie, Halban, and Bishop, Rev. Sci. Inst. to be published (1950).

the pressure has to be reduced to 1.5 atmos. in order to reduce the background. (At the same time the pulse shaping time constants were readjusted to the optimum values.)

The counter pressure was measured by expanding the deuterium into a known volume and measuring the pressure on a mercury manometer. Great care was taken with the temperature corrections, and 0.1 percent accuracy is estimated here.

### F. Hydrogen Impurity

The percentage of hydrogen impurity in the deuterium was greater than that found before in our electrolysis plant, due to slight changes in the use of the plant. For each counter filling this was measured on a mass spectrometer which has an estimated accuracy of 0.1 percent in the total deuterium content; this accuracy was checked by the measurement of samples of the same gas composition on other mass spectrometers (in Paris and in Chalk River). The agreement was better than 0.1 percent.

### G. Gamma-Ray Absorption

The absorption of $\gamma$-rays in the sources and counter varied. The sodium source used for the absolute calibration was of a thin rectangular shape (2 cm$\times$2 cm $\times$0.4 cm). The total absorption of $\gamma$-rays for the source and the aluminum holder was 0.5 percent.

The radiothorium source used for the absolute calibration (200 mc) was made on a $ThO_2$ carrier, mixed with platinum black. The whole is enclosed in a cylindrical container with 1/10-mm platinum wall. The absorption in this container is about 10 percent. Some of this absorption is due to Compton scattering; not all degraded quanta from Compton scattering will produce photo-disintegration but all will produce ionization in the ionization chamber. The difference in the absorption for the calibration and for the use for photo-disintegration experiments is 1 percent and is applied as a correction.

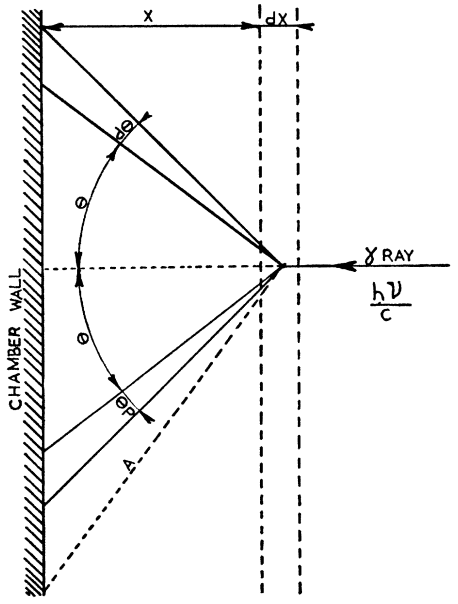


FIG. 7. Geometry of the wall effect corrections. Limits of $\theta$ from 0 to $\cos^{-1}(x/A)$, $A$ is the average range of the photo-protons. Limits of $x$ from 0 to $A$.

For the relative cross-section measurements, sources of sodium carbonate, gallium metal, and radiothorium (this time on $Al_2O_3$ as carrier) were placed in identical copper cylinders, 4 mm diameter and 18 mm long, with a wall thickness of 1.5 mm. The total absorption of $\gamma$-rays in the copper container is approximately the same (5 percent) for each source, but the absorption of $\gamma$-rays in the source material will differ (from 0.5 percent for sodium carbonate to 3 percent for gallium metal). However, we are only concerned with the number of $\gamma$-rays which escape from the source; the $\beta$-spectrometer calibration takes no account of those which are absorbed in the source or the source walls. This absorption enters thus into both the calibration and the use of the sources and can therefore be neglected. There is a difference in sensitivity of the $\beta$-ray spectrometer and the photo-disintegration counter for $\gamma$-rays slightly degraded by Compton scattering. This leads to a second-order correction of about 0.05 percent and has been neglected. The absorption of $\gamma$-rays in the wall of the counter has been reduced by making the walls of stainless steel 0.5 mm thick, soldered on to mild steel ends. The inner spherical electrode is of aluminium, 0.2 mm thick, 4 cm diameter. The absorption in these is calculated to an accuracy of 0.1 percent of the final intensity.

The ends of the counter, and the supporting rod from the counter to the source, are massive for rigidity; this and other massive material were so placed that any $\gamma$-rays scattered into the counter were scattered through more than 12° and were therefore degraded in energy below the threshold for photo-disintegration of deuterium.

### H. Wall Effect Corrections

The correction due to the wall effect is considerable and must be considered carefully. At even the highest pressures used (8 atmos.) 6 percent of the photo-protons lost part of their range in the walls, and thus had less probability of being counted. When counting the low energy protons from radiogallium the pressure had to be reduced to 2 atmos. in order to reduce the background of secondary electrons, with a corresponding increase (to 15 percent) in the wall effect.

The problem can be approached in two ways. The theoretical value may be taken assuming the range-energy relationship for protons in deuterium. The form of this curve has been derived from measurements of the stopping power of $H_2$ or $D_2$ gas for protons made by Crenshaw.[46] This curve agrees well with the Livingston-

[46] C. M. Crenshaw, Phys. Rev. **62**, 54 (1942).

TABLE I. Sodium source $Na^{24}$.

| Date of measurement | $[C_p z]$ | $V$ (cm³) | $P$ (atmos.) | $R$ | $S$ |
|---|---|---|---|---|---|
| November 28, 1949 | $3.7701\times10^{4}$ | 28.59 | 7.663 | 0.1705 | $2.544\times10^{-16}$ |
| December 19, 1949 | $4.119\times10^{4}$ | 28.59 | 7.107 | 0.2053 | $2.495\times10^{-16}$ |
| February 27, 1950 | $6.213\times10^{4}$ | 28.54 | 4.927 | 0.4480 | $2.550\times10^{-16}$ |
| March 6, 1950 | $8.894\times10^{4}$ | 28.54 | 7.236 | 0.4347 | $2.528\times10^{-16}$ |
| | Average $S=(2.529\pm0.017)\times10^{-16}$ | | | | |

TABLE II. RdTh source.

| Date of measurement | $[C_p z]$ | $V$ (cm³) | $P$ (atmos.) | $R$ | $S$ |
|---|---|---|---|---|---|
| November 28, 1949 | $1.964\times10^{5}$ | 28.59 | 7.663 | 0.8723 | $2.603\times10^{-16}$ |
| January 27, 1950 | $1.170\times10^{5}$ | 28.59 | 4.963 | 0.8198 | $2.590\times10^{-16}$ |
| February 3, 1950 | $1.268\times10^{5}$ | 28.59 | 5.401 | 0.8141 | $2.582\times10^{-16}$ |
| | Average $S=2.592\times10^{-16}\pm0.012$ | | | | |

TABLE III. Na Source.

| Date of measurement | $N$ | $R$ | $T$ |
|---|---|---|---|
| March 28, 1950 | $11.28\times10^{10}$ | 0.7107 | $15.87\times10^{10}$ |

TABLE IV. Intensity measurements.

| Date of measurement | Isotope | Run | Corrected area of photo-line | Relative $\gamma$-ray intensity |
|---|---|---|---|---|
| | $Na^{24}$ | 1 | 262.1 | |
| | (2.757 Mev) | 2 | 277.2 | 1.591 |
| I | ThC″ | 1 | 180.2 | |
| November 14, 1949 | (**2.618 Mev**) | 2 | 180.4 | **1** |
| 9:00 GMT | $Ga^{72}$ | 1 | 655.2 | |
| | (2.504 Mev) | 2 | 659.5 | 3.450 |
| | $Na^{24}$ | 1 | 185.1 | |
| | | 2 | 180.3 | 2.302 |
| II | ThC″ | 1 | 83.6 | |
| January 16, 1950 | | 2 | 86.0 | **1** |
| 9:00 GMT | $Ga^{72}$ | 1 | 427.3 | |
| | | 2 | 421.5 | |
| | | | 427.9 | 4.76 |
| | $Na^{24}$ | 1 | 273.1 | |
| III | | 2 | 272.0 | 3.452 |
| March 20, 1950 | ThC″ | 1 | 83.0 | |
| 9:00 GMT | | 2 | 85.6 | **1** |
| | $Ga^{72}$ | 1 | 423.3 | |
| | | 2 | 423.7 | 4.76 |

Bethe curve for protons in air, using the relative stopping powers of $H_2$ and air, compiled by Gray.[47] Recent confirmation of this curve has come from the study of the $N^{14}(n,p)C^{14}$ reaction by Cornog.[48] The calculation is complicated by two factors: the energy spread of the photo-protons due to the conservation of momentum, and the form of the range-energy relation. However, assuming an isotropic distribution and a fixed range equivalent to the average energy of the photo-protons, we calculate the number of photo-protons having their range terminated by the wall. For a plane wall and range $S$, there are all those protons ejected into a cone defined by $\theta$ from 0 to $\cos^{-1}(x/S)$, (Fig. 7). The total number of protons affected is then found by integrating this expression from $x=0$ to $x=S$. This gives $\frac{1}{4}NS$ where $N$ is the number of photo-protons formed per unit volume. For a spherical counter of radius $R$ the percentage of ranges affected is then $(3S/4R)\times100$ which may be written

$$I=(\text{surface area/volume})\times\text{range}\times\tfrac{1}{4}.$$

A correction for the spherical geometry is easily evaluated and the expression found is

$$\text{percentage of counts affected}=\frac{3}{2R}\left(\frac{S}{2R}-\frac{S^3}{24R^3}\right)\times100.$$

Thus for $S\ll R$ (i.e., high pressure), the correction is negligible. A further calculation for spherical geometry, correcting for the energy spread and range-energy relation and using an analytic expression for the stopping power, yields results in agreement with the simple formula. If we count protons having an energy of $\geq140$ kev say, determined by the bias setting, and the average photo-proton energy is 290 kev, then the percentage of the photo-protons not counted is

$$[(3/4R)(S_{290}-S_{150})\times100](\text{percent}),$$

where $S_{290}$ and $S_{150}$ are the ranges for 290-kev and 150-kev protons respectively. The value $S_{150}$ arises because protons which lose 150-kev range in the walls will *just* be counted. We must therefore subtract from the simple expression those protons which lose 150 kev or less. The energies of the photo-protons are calculated from the $\gamma$-ray energies, assuming a binding energy[49] of 2.23 Mev.

Alternatively, an empirical approach may be adopted, by using the measured wall effects at low counter pressures to correct the measurements at higher pressures. This empirical method yields results in complete agreement with the values expected from the above calculations.

The counters were operated at a sufficiently high potential to make the loss of pulse height due to incomplete positive ion collection small. This was shown by the shape of the pulse height distribution curve which was nearly symmetrical. There was a low energy "tail" to this curve but, over the range of discriminator bias values used for the cross-section measurements, this tail was entirely due to those protons which lost some

[47] L. H. Gray, Proc. Camb. Phil. Soc. **40**, 72 (1944).

[48] Corneg, Franzen, and Stephens, Phys. Rev. **74**, 1 (1948).

[49] This value was sent to us by Dr. W. B. Lewis. It is a correction by R. E. Bell and L. B. Elliott of their value 2.237 Mev published in Phys. Rev. **74**, 1552 (1948). This also agreed well with the value of the binding energy 2.224 Mev deduced from the neutron-hydrogen mass difference 782±2 kev found by Taschek, Argo, Hemendinger, and Jarvis, Phys. Rev. **76**, 325 (1949) and other transmutation cycles, combined with the mass spectrographic doublet 2H−D found by T. R. Roberts and A. O. C. Nier, Phys. Rev. **77**, 746 (1950).

For purposes of $\gamma$-ray measurements it is preferable to take the value of Bell and Elliott based on the energy of the ThC″ $\gamma$-ray line as a standard. A decrease in the binding energy of the deuteron would, however, reduce the discrepancy between theory and experiment.

TABLE V. Photo-proton counting rate and substandard comparisons.

| Measurement | | I.C.C. Measurements Photo-proton counting rate | Corrected photo-proton counting rate | Substandard comparisons Ionization Oxford source relative to radium source | Ratio Stockholm source to Oxford source |
|---|---|---|---|---|---|
| I | Na | 81.1 | 92.1±1 | 3.244 | 0.9806 |
| November 14, 1949 | RdTh | 45.1 | 50.2±0.5 | 1.610 | 1.000 |
| 9:00 GMT | Ga | 128.1 | 139.5±1.4 | 1.982 | 1.058 |
| II | Na | 74.33 | 85.18±1 | 4.464 | 1.032 |
| January 16, 1950 | RdTh | —— | 32.80[a] | —— | 1.000 |
| 9:00 GMT | Ga | 104.5 | 114.5±1.2 | 24.44 | 1.149 |
| III | Na | 140.3 | 164.1±1.6 | 6.248 | 1.027 |
| March 20, 1950 | RdTh | 36.43 | 41.45±0.4 | 1.435 | 1.000 |
| 9:00 GMT | Ga | 151.1 | 168.6±1.7 | 25.91 | 1.059 |
| IV | Na | 229.2 | 240.5±2 | 5.541 | 0.8314[b] |
| February 13, 1950 | RdTh | 69.7 | 72.44±0.7 | 1.480 | 1.028[b] |
| 9:00 GMT | Ga | —— | ± | —— | —— |

[a] Calculated from RdTh counting rate in experiment (I) using the known counter pressures and source distances; the RdTh source was still in Stockholm so no separate count was made.
[b] Ratio of the Stockholm source of experiment (II) calculated from the ratios to the radium standard (correct to 9:00 on the respective mornings). The ratio of cross sections was calculated using the Stockholm figures for experiment (II).

of their energy in the walls. The value of the "differential" counting rate at these bias values was in complete agreement with the value to be expected from the wall effect calculations. If any appreciable loss of pulse height by positive ions had been occurring, this agreement would not have been reached. We estimate, therefore, that we are justified in correcting by the wall effect calculations alone for those protons which give too small a pulse to be recorded.

For the absolute cross section all of these errors appear directly, but for the relative cross sections some of them tend to cancel. The positive ion effect was actually observed by comparing the rise and decay times of the pulses with equal time constants of differentiation and integration. The most significant source of error for the relative cross sections is the wall effect. By counting the photo-protons from each source at the same discriminator bias, the error is minimized. The correction would be zero if the range-energy relationship were linear; the small non-linearity introduces a difference of 1.5 percent (which can be assessed to 0.1 percent).

For the absolute measurements, the wall effect correction is about 6 percent which is assessed to within 0.2 percent.

## V. RESULTS

### A. Absolute Cross Sections

The results from individual measurements are given in the following tables. In Tables I and II we give the results of photo-proton counting using a parameter $S$ given by the expression

$$S=\{4\pi[C_p^2]/2LVP\}\times(1/R),$$

where $[C_p^2]$=counting rate × inverse square of distance between source and I. C. C. corrected for finite size of source and sensitive volume, $L$=Loschmidt's number, $V$=volume of counter, $P$=pressure in the chamber reduced to 0° measured in atmospheres, $R$=ratio of total activities of the source and standard Radium source as measured on the Curie chamber. Corrections are applied for (a) atomic percent of $H_2$ in the deuterium gas, (b) wall effect for the particular measurement, (c) absorption in source, source container, and walls of I.C.C. In Table III we give the results for absolute calibration of the sodium sources, using a parameter $T$ defined by $T=N/R$ where $N$ is the number of disintegrations/min. of the source, and $R$ is the same factor as described in Table I. Then the mean value of $S$ divided by the mean value of $T$ is the photo-disintegration cross section $\sigma_{2.76}$ for radiosodium $\gamma$-rays. For radiothorium we take the value of the parameter $T$, given by the results of Bouchez,[40] assuming the effective intensity of our radium standard (N.P.L. certificate RG 467) to be known.[50]

We have then,

$$\sigma_{2.76}=(15.9\pm0.4)\times10^{-28}\ \text{cm}^2,$$
$$\sigma_{2.62}=(13.8\pm0.4)\times10^{-28}\ \text{cm}^2$$

and

$$\sigma_{2.76}/\sigma_{2.62}=1.17\pm0.06.$$

TABLE VI. Relative cross sections.

| Measurement | $\sigma_{2.76}/\sigma_{2.804}$ | $i\sigma_{2.76}/\sigma_{2.618}$ | $\sigma_{2.618}/\sigma_{2.804}$ |
|---|---|---|---|
| I | 1.327 | 1.131 | 1.175 |
| II | 1.382 | 1.164 | 1.187 |
| III | 1.302 | 1.178 | 1.105 |
| IV | | 1.166 | |
| Mean | 1.337 | 1.159 | 1.156 |

[50] A small correction must be applied; the National Physical Laboratory specifies the effective value of the radium source as measured on their ionization chamber in which the $\gamma$-rays pass normally through 5-mm Pb. In our chamber the $\gamma$-rays pass, some of them obliquely, through 10-mm Pb and the absorption of soft radiation in the source container and carrier is less important. We evaluated this correction of 1.8 percent from the results of Kaye, Aston, and Perry, Brit. J. Radiol. 7, 540 (1934).

The errors given here are those of the reproducibility of the measurements.

### B. Relative Cross Sections

The results are presented in two sections; Table IV shows the results of the intensity measurements on the spectrometer in Stockholm and Table V shows the results of the photo-proton counting and the substandard comparisons. All figures are corrected for source decay to 9:00 GMT on the day of measurement (±10:00 Swedish time). By division of the figures in these tables, the relative cross sections of Table VI are obtained.

### C. Discussion of Errors

#### (*a*) *Accuracy of Intensity Measurements*

The largest deviation between two intensity measurements on one line occurred in the first sodium measurements and amounted to ±3 percent from the mean value. In all other cases the reproducibility is much better. Taking into consideration the combined results from the substandard ionization chamber measurements and the corresponding spectrometer results at different times we estimate the non-systematic errors in the $\gamma$-ray intensity measurements to be 2 percent. Additional systematic errors may be difficult to eliminate but judging from our experiments on the two $\gamma$-lines of sodium it seems unlikely, according to the previous discussion, that systematic errors should exceed 2 percent within our small energy range. If a correction of this magnitude due to a small departure from Eq. (1) should be applied to our final results, the photo-disintegration cross section would have a somewhat *smaller* slope, thus accentuating the disagreement with theory which appears later. We believe, however, that this correction should not be applied, since the correction may very well be smaller. The small gallium correction (1 percent) discussed above is probably accurate to $\frac{1}{2}$ percent.

#### (*b*) *Consistency of Oxford Measurements*

This is best illustrated by comparison of the results of individual measurements; taking the ratios of photo-proton counts for each pair of sources and dividing by the corresponding ratio as determined on the substandard ionization chamber (Tables VII and VIII). Since the photo-porton comparison is made with the same source to counter distance, and the same counter pressure for each source in the same measurement, the errors incurred in the determination of these are eliminated. The agreement is 0.3 percent, which is within the statistical error of counting.

A further comparison has been made by a reduction of the individual counting rates (instead of the ratios) to unit pressure and distance. The agreement is better than 0.6 percent, showing that the measurement of distance, and counter pressure, $D_2$ content, and source decay errors are small. The errors due to wall effect uncertainty and $\gamma$-ray absorption will be systematic errors and will not enter into this calibration. The total uncertainty of the photo-proton counting is estimated as 1 percent.

TABLE VII. Relative photo-proton and ionization (Na/Ga) counts.

| Measurement | Photo-protons Na/Ga | Ionization Na/Ga | Photo-protons/unit ionization Na/Ga |
|---|---|---|---|
| I | $\frac{92.1}{139.5}=0.6604$ | $\frac{3.244}{19.82}=0.1636$ | $\frac{0.6604}{0.1636}=4.035$ |
| II | $\frac{85.72}{115.4}=0.7429$ | $\frac{4.492}{24.44}=0.1839$ | $\frac{0.7429}{0.1839}=4.041$ |
| III | $\frac{164.1}{168.6}=0.9736$ | $\frac{6.248}{25.91}=0.2411$ | $\frac{0.9736}{0.2411}=4.037$ |

TABLE VIII. Relative photo-proton and ionization (Na/Th) counts.

| Measurement | Photo-protons Na/Th | Ionization Na/Th | Photo-protons/unit ionization Na/Th |
|---|---|---|---|
| I | $\frac{92.12}{50.2}=1.835$ | $\frac{3.244}{1.61}=2.006$ | $\frac{1.835}{2.006}=0.9109$ |
| IV | $\frac{214.5}{72.54}=2.956$ | $\frac{4.935}{1.48}=3.334$ | $\frac{2.956}{3.334}=0.9078$ |
| III | $\frac{164.1}{41.45}=3.961$ | $\frac{6.248}{1.435}=4.354$ | $\frac{3.961}{4.354}=0.9097$ |

## VI. FINAL RESULTS AND COMPARISON WITH THEORY

### A. Theoretical Cross Sections

One can calculate the theoretical cross section either by a meson theory, as has been done by Hansson and Hulthén[14] or by the phenomenological theory of Bethe and Longmire.[15] If coherent neutron-proton scattering data are used to determine the meson mass or effective range respectively, both theories must give the same result. The best experimental data for these calculations are the following:

(a) meson mass[51] $=(277\pm7)m_e$,
(b) binding energy of the deuteron[49] $=2.231\pm0.005$ Mev,
(c) effective range of force in the $n-p$ triplet state[52] $r_t=(1.71\pm0.04)\times10^{-13}$ cm,
(d) free proton scattering cross section for neutrons[53] $=20.32\pm0.01$ barns,

[51] This was calculated by Professor Hulthén from the experiment of neutron reflection by a liquid mirror. Hughes, Burgy, and Ringo, Phys. Rev. **77**, 291 (1950). It agrees well with the mass of the $\pi$-meson (276±6) em. Smith *et al.*, Phys. Rev. **78**, 86 (1950).

[52] Also obtained from the experiment of neutron reflection by a liquid mirror. Hughes, Burgy, and Ringo, Phys. Rev. **77**, 291 (1950).

[53] E. Melkonian, Phys. Rev. **76**, 1744 (1950).

TABLE IX. Photo-disintegration cross section of the deuteron.

| | Experiment | Theory |
|---|---|---|
| $\sigma_{2.757}\times10^{-27}$ cm$^2$ | 15.9±0.6 | 15.1±0.3 |
| $\sigma_{2.618}\times10^{-27}$ cm$^2$ | 13.9±0.6 | 12.5±0.3 |
| $\sigma_{2.757}/\sigma_{2.504}$ | 1.34±0.05 | 1.49±0.02 |
| $\sigma_{2.618}/\sigma_{2.504}$ | 1.16±0.04 | 1.24±0.01 |
| $\sigma_{2.504}\times10^{27}$ cm$^2$ | 11.9±0.8 | 10.1±0.3 |

(e) neutron-proton capture cross section[54]
$\sigma_{cap}=(0.310\pm0.02)$ barn,
(f) energies of $\gamma$-rays used (obtained from Table IV)
2.757, 2.618, 2.504 Mev.

For the meson theory we use (a), (b), (d), and (f) since the capture cross section can be uniquely determined, in a meson theory, by these data. For a phenomenological theory we use the data (b) to (f) inclusive.

We have taken Hansson and Hulthén's[14] results, for a zero interaction in the $P$-state, and have interpolated to obtain the result for a meson mass 277; we have also adjusted the values for the small changes in the $\gamma$-ray energies and the binding energy of the deuteron. Bethe and Longmire's calculations when adjusted for the new experimental data given above, lead to values of the total cross section lower by about 2 percent.

There remain some uncertainties in the theory. If a non-zero interaction in the $P$-state is assumed, the photoelectric component of the cross section would be altered by up to 2 percent, the direction depending on the sign of the interaction.[14,15] The contribution of exchange currents to the magnetic moment of the deuteron, which appear in a charged meson theory, would change $\sigma_m$ and $\sigma_{cap}$ by an uncertain amount. Hansson and Hulthén[14] have shown that this effect is negligible if the Møller-Rosenfeld theory is assumed, but for other charged meson theories no theoretical calculations are available; accurate calculations are difficult because a cut-off procedure must be adopted. Professor Hulthén informs us however that it is unlikely that the *energy dependence* of the photo-magnetic effect would be appreciably altered by the existence of exchange currents.

[54] W. J. Whitehouse and G. A. R. Graham, Can. J. Research **A25**, 261 (1947). Dr. Whitehouse informs us that he attributes a possible systematic error of 4 percent to this result due partly to the uncertainty of the boron composition and partly to the finite size of the boron chambers used as neutron detectors; the total uncertainty in $\sigma_{cap}$ becomes 8 percent.

## B. Tabulated Results

For our experimental results (Tables IX) we attribute in addition to statistical errors possible systematic errors of 3 percent to the absolute cross section using ThC″, 2 percent using $Na^{24}$ and 2 percent to the relative cross section.

## C. Discussion

Our results could possibly indicate a divergence from theory, increasing as the energy decreases. Better agreement would be obtained if the theoretical photo-magnetic cross section were increased (by exchange currents for example). This is also suggested by measurements of the angular distribution of photo-neutrons.[55–60]

A definite limit to this possibility is given by the capture cross section.[54] The experimental value (0.310 ±0.02 barn) is very close to the theoretical value (0.315±0.003 barn). An increase of $\sigma_{cap}$ by 10 percent, the limit of uncertainty of the experimental value, would be permissible.

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[55] G. A. R. Graham and H. Halban, Rev. Mod. Phys. **17**, 297 (1945).
[56] N. O. Lassen, Phys. Rev. **74**, 1533 (1948); **75**, 1099 (1949).
[57] W. M. Woodward and I. Halpern, Phys. Rev. **76**, 107 (1949).
[58] E. P. Meiners, Phys. Rev. **76**, 259 (1949).
[59] B. Hamermesh and A. Wattenberg, Phys. Rev. **76**, 1408 (1949).
[60] F. Genevese, Phys. Rev. **76**, 1288 (1949).